CLFV in heavy state decays at colliders

Summarizing experimental part of Snowmass white paper

Charged Lepton Flavour Violation in Heavy Particle Decays

arXiv:2205.10576

with contributions from

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Seattle Snowmass Summer Meeting 2022

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Niels Bohr Institute, Copenhagen
21st July, 2022

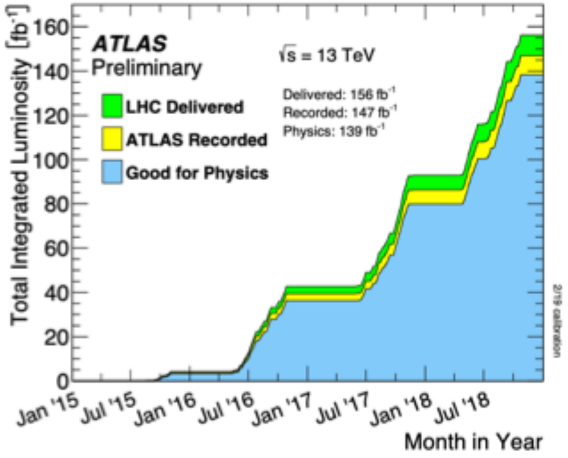
Outline

- Experimental situation
- Z decays
- Higgs decays
- Top quark production and decays
- Summary

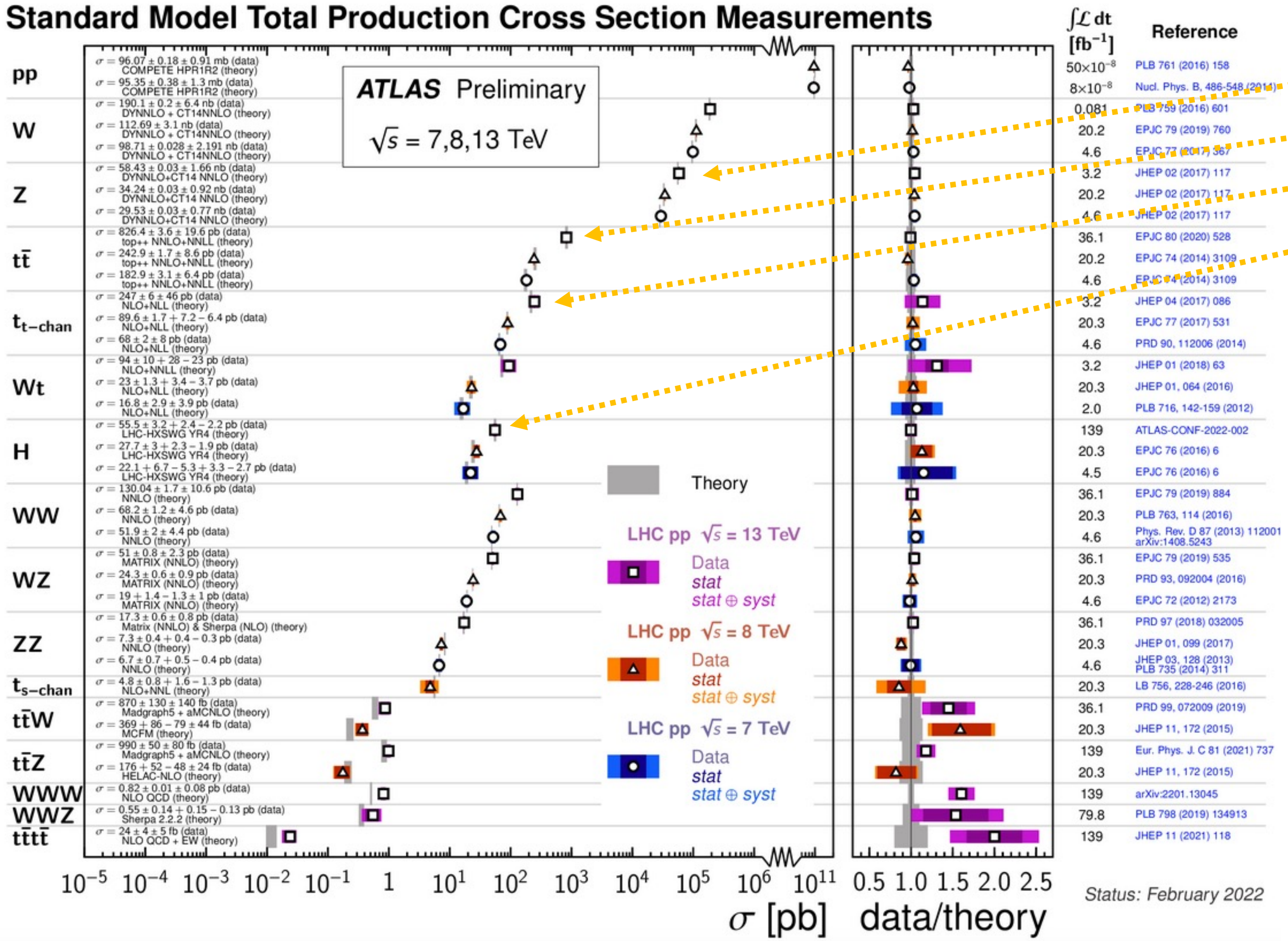
Experimental situation

The LHC Situation

About 140 fb^{-1} have been collected at √s = 13 TeV in Run 2 (2015-18) **×** **Production cross sections** **=** **Large data samples**



End of HL-LHC: 3000 fb^{-1}



8 × 10^9 Zs
1 × 10^8 ttbar
3 × 10^7 single top
7 × 10^6 Higgs

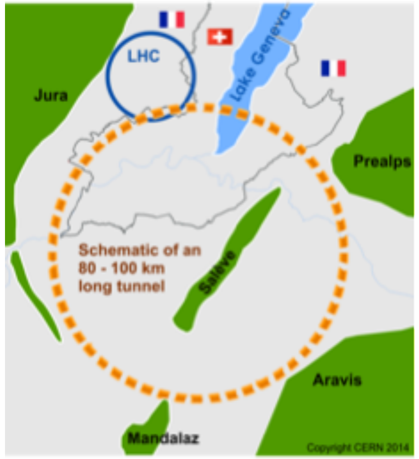
Lots of events in which to search for LFV effects.

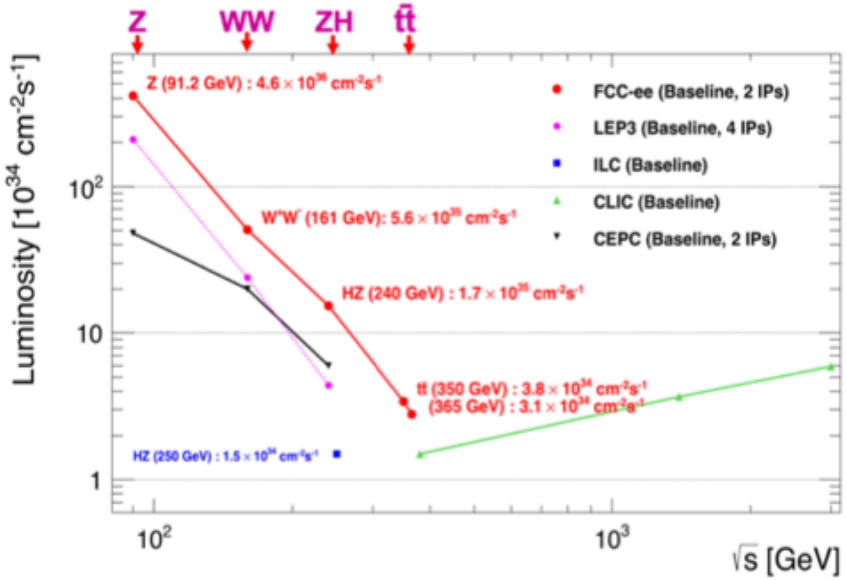
High backgrounds and less powerful kinematic constraints limit the per event sensitivity

⇒ Resorting to sophisticated algorithms (e.g. Machine Learning).

Future Circular*) e^+e^- Collider

- FCC-ee, if constructed, will have an enormous instantaneous luminosity.
  - At the Z pole, **10^5** times higher than LEP.
- Luminosity falls off with √s due to synchrotron radiation





During a 15 year's running period, FCC-ee will deliver

5×10^{12} $e^+e^- \longrightarrow Z$
10^8 $e^+e^- \longrightarrow W^+W^-$
10^6 $e^+e^- \longrightarrow HZ$
10^6 $e^+e^- \longrightarrow tt$

The Z statistics exceed that of HL-LHC by more than ×10.
Statistics less than LHC for Higgs (×1/100) & top (×1/10)

Experimental conditions will be very clean ⊕ strong kinematic constraints are imposable.

- Even with less events, senitivities may be better.

FCC Integraded Programme:

- Stage 1: Very high luminosity e^+e^- collider Z, WW, HZ, tt factory
- Stage 2: 100 TeV proton-proton collider

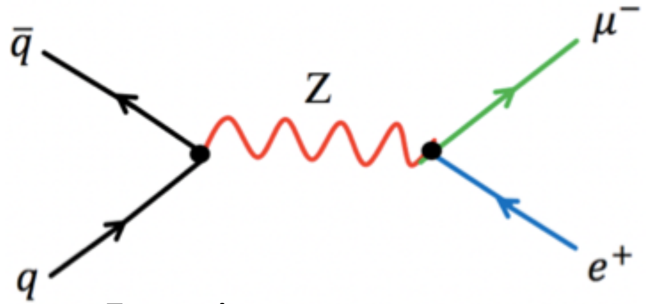
	LHC Run 2	HL-LHC	FCC-ee
Z bosons	8×10^9	1.7×10^{11}	5×10^{12}
Higgs bosons	7×10^6	1.6×10^8	1.2×10^6
top quarks	2.2×10^8	5×10^9	2×10^8

)* I will here touch mainly on circular e^+e^- colliders due to their superiour event statistics compared to linear colliders

Z Decays

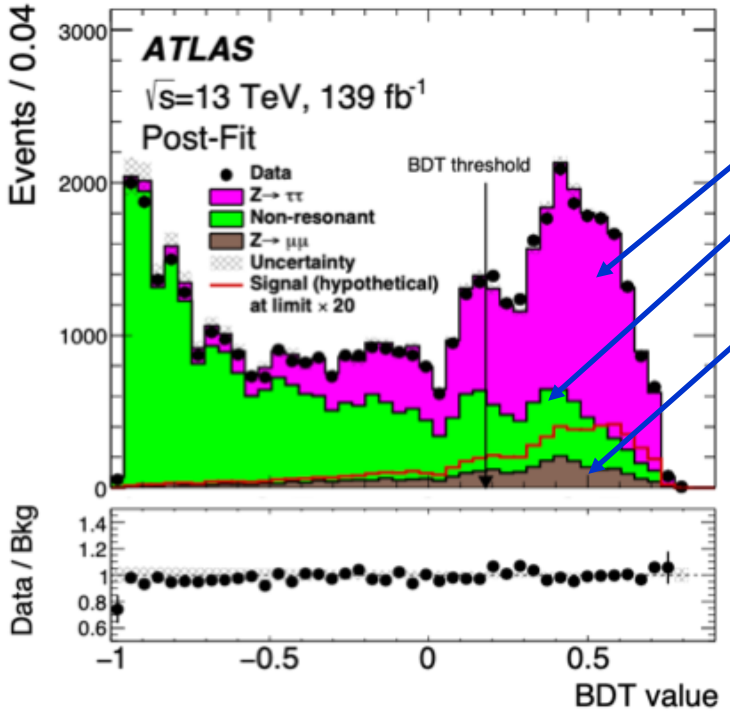
$Z \to e\mu$ @ LHC

ATLAS Analysis from full Run-2 dataset [1]



Easy signature:

- Look for bump in $e\mu$ mass distribution



Event selection:

- Oppositely charged $e\mu$ pair with mass in window $70 < m_{e\mu} < 110$ GeV
- Machine learning BDT trained on leading jet p_T, E_T^{miss}, and $p_T^{e\mu}$

$\Rightarrow$ Signal acceptance × efficiency: 10.3%

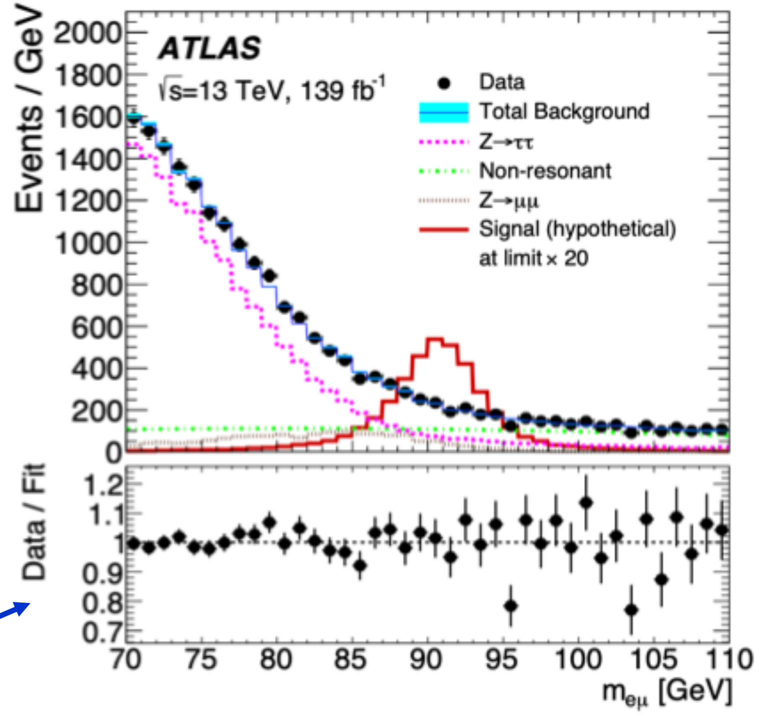
Backgrounds:

- $Z \to \tau\tau \to e\mu + 4\nu$, where all νs are soft
- Non-resonant (di-boson, top quark single or pair, $W \to \ell\nu$)
- $Z \to \mu\mu$, with one μ misidentified as e (hard brems in ECAL)

Result:

From fit to $m_{e\mu}$ distribution of 7.9×10^9 Z decays, set 95% CL branching fraction limit

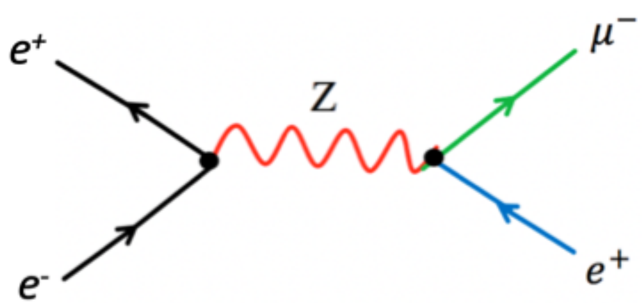
$\mathcal{B}(Z \to e\mu) < 2.62 \times 10^{-7}$



HL-LHC projection:

- ×20 data from HL-LHC: $\sim 5 \times 10^{-8}$
- Contribution from CMS(?)

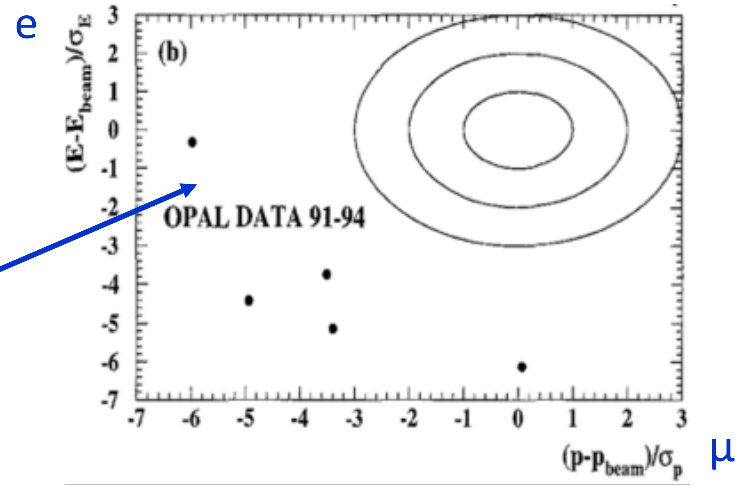
Z → eμ @ e+e- colliders : LEP & FCC-ee



Extremely clean signature:
- Beam energy electron recoiling against beam energy muon

OPAL@LEP: Background free search from 4×10^6 Z decays

$\boxed{\mathcal{B}(Z \to e\mu) < 17 \times 10^{-7}}$



[2]

FCC-ee

- 5-6 orders increased Z statistics w.r.t LEP
- Modern detectors: Momentum resolution improved by more than one order w.r.t. LEP: $\mathcal{O}(10^{-3})$ at 45.6 GeV
- Inv. mass, $m_{e\mu,}$ constrained to 10^{-3} level from low beam energy spread

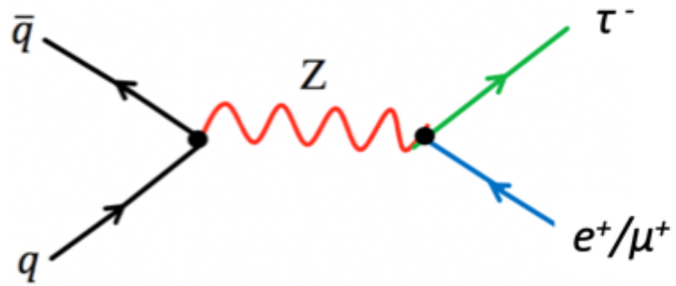
⇒ Signal will stand as a 2D "delta function" on top of the falling background tail from $Z \to \tau\tau \to e\mu$ + neutrinos. Only for more than 10^{11} Z decays will $Z \to \tau\tau$ background start to appear.

Main experimental challenge believed to be: $Z \to \mu\mu$ with hard bremsstrahlung of μ in ECAL material ⇒ μ fakes e

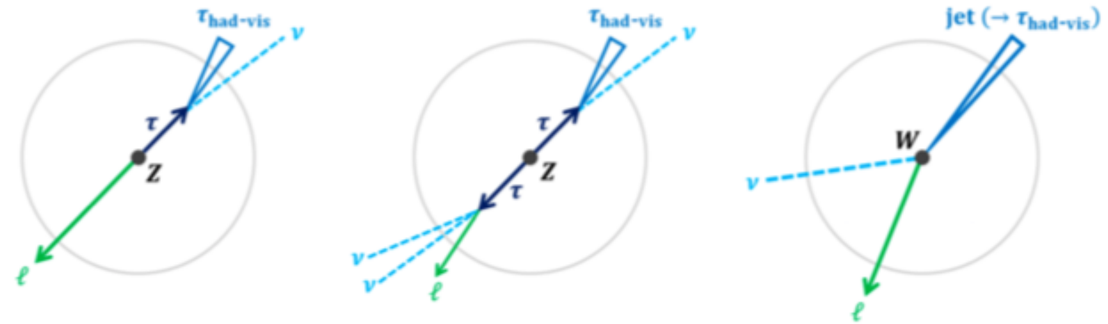
From NA62 measurements: Expect this background to appear at $\mathcal{B} = 10^{-8}$ level.
Situation can be controlled by
- Longitudinal ECAL segmentation (shower shape)
- Independent means of e/μ separation: dE/dx (dN/dx)

Without (with) dE/dx, may reach $\mathcal{B}$ level of 10^{-9} (10^{-10}) [3]

$Z \to e\tau, \mu\tau$ @ LHC (i)

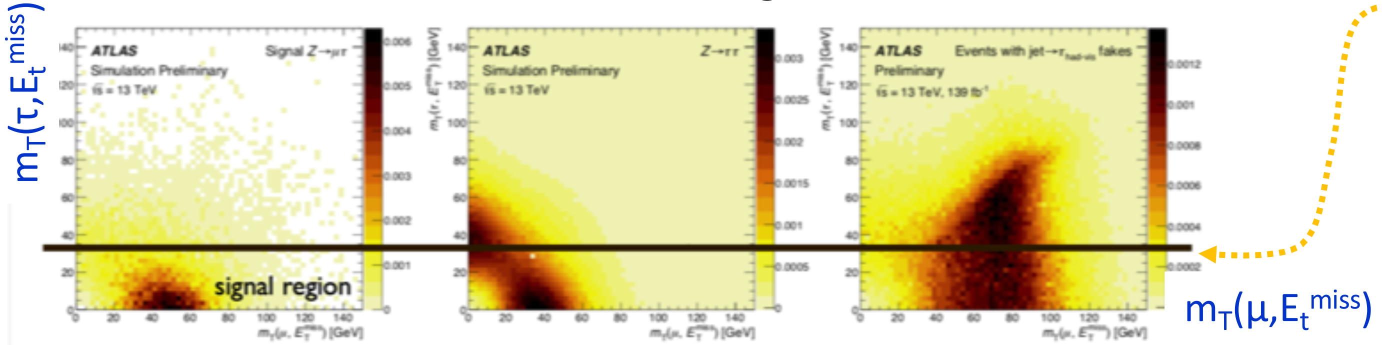


Signal and backgrounds not well separated:
⇒ Exploit all possible available event information
⇒ **Machine Learning – Neural Network - NN**



signal

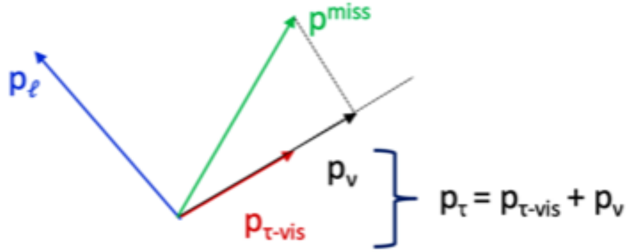
backgrounds



ATLAS Analysis from full Run-2 dataset [4,5]

Mass of $\ell\tau$ system from **collinear approximation:**

- Assume that neutrino direction is parallel to visible tau decay products direction
- In transverse plane, project *missing momentum* vector onto tau direction ⇒ neutrino momentum



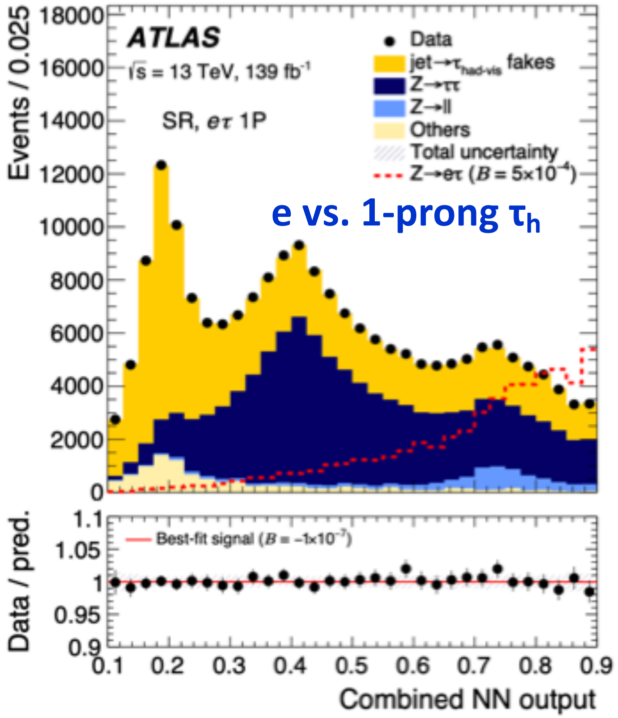
Event selection strategy:

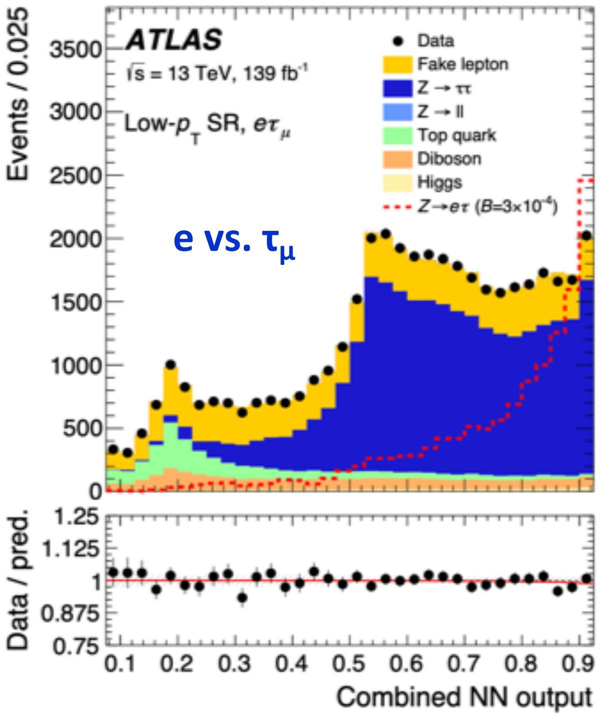
- Oppositely charged ℓ and τ
- $m_T(\ell,E_t^{miss}) < 35$ GeV & $m_{vis}(\ell,\tau) > 60$ GeV
- Cut on combined NN output based on
  - NN1 from low level variables (e.g. momentum components)
  - NN2 from high level variables (e.g. $m_{col}(\ell\tau)$)

Z → eτ, μτ @ LHC (ii)

ATLAS Analysis from full Run-2 dataset [4,5]

Examples of combined NN distributions





Combined analysis (two separate papers) exploiting as well hadronic, τ_h, as leptonic, τ_ℓ, tau decays

Results: 95% CL limits

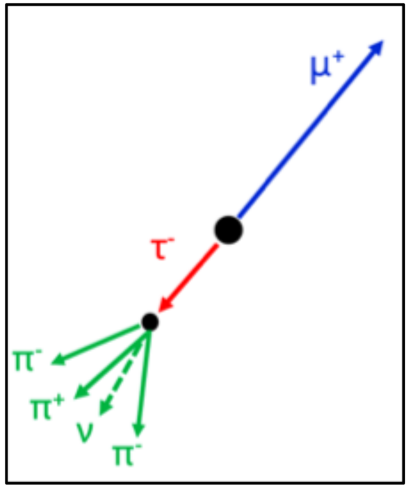
$\mathcal{B}(Z \to e\tau) < 5.0 \times 10^{-6}$ & $\mathcal{B}(Z \to \mu\tau) < 6.5 \times 10^{-6}$

Notice: ×20 weaker limit than for eμ search

HL-LHC projection:

- ×20 data from HL-LHC: Possibly reach $\sim 10^{-6}$
- Contributions from CMS(?)

Z → eτ, μτ @ e^+e^- colliders : LEP & FCC-ee



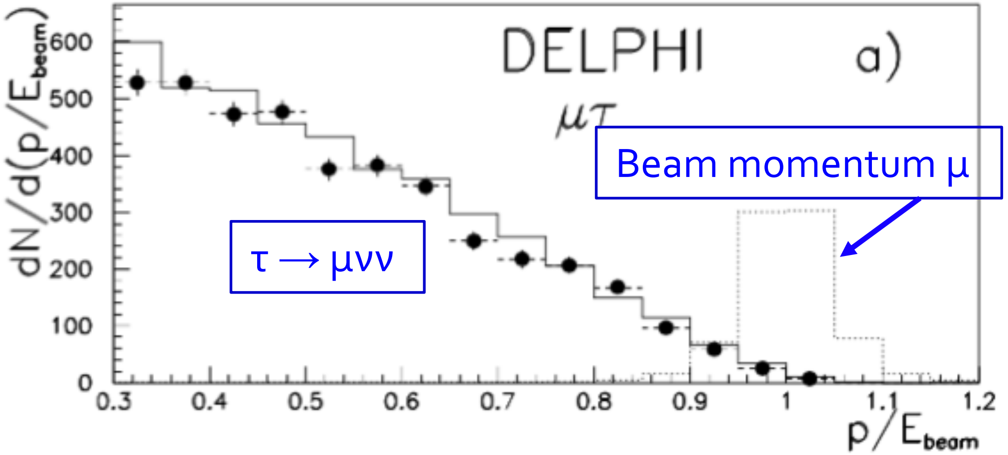
Search method at e^+e^- colliders:

- Identify *clear tau decay* in one hemisphere
- Look for *"beam-energy" lepton* (ℓ = e or μ) in other hemisphere

Limitation: How to define *"beam-energy" lepton*

- Unavoidable background from $\tau \to \ell\nu\nu$ / with two (very) soft neutrinos
- Background level depends on momentum resolution

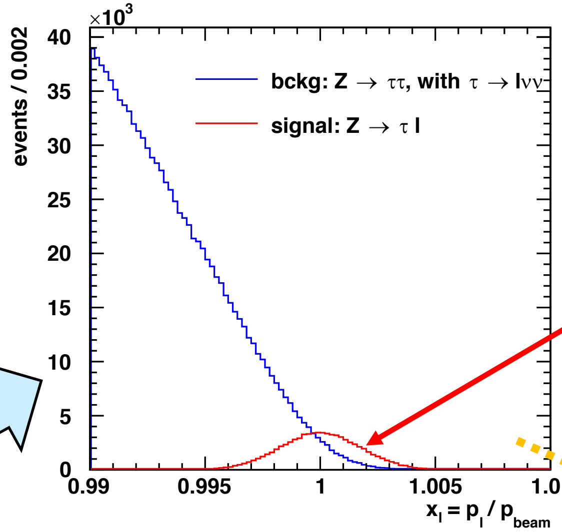
Example DELPHI: Z.Phys. C73



[6]

At FCC-ee, conditions much much more favourable

- 5-6 orders higher statistics
- Better momentum resolutiuon by factor $\mathcal{O}(10)$



[3]

For illustration, signal at $\mathcal{B}(Z \to \ell\tau) = 10^{-7}$ injected

Notice:

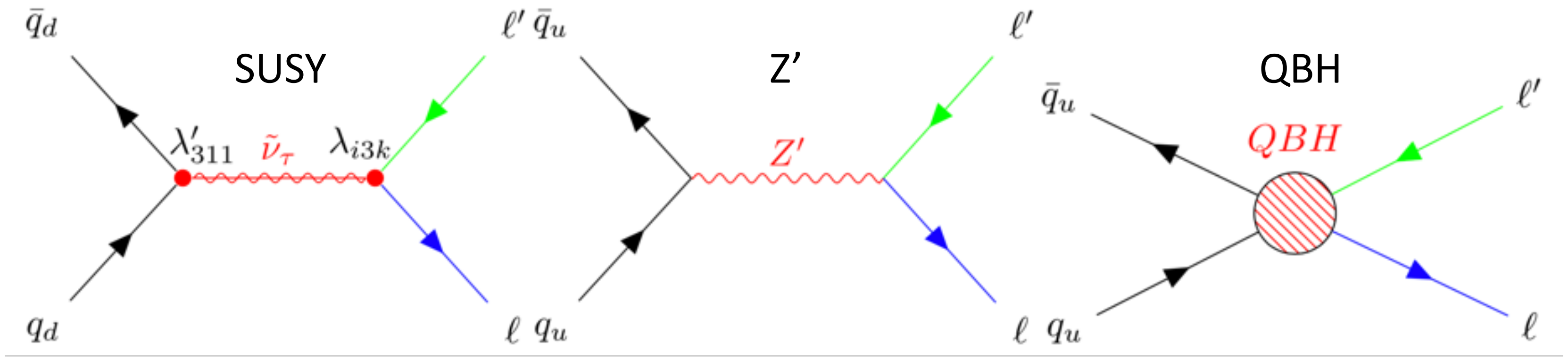
- Very different horizontal axis: much better resolution
  - Only uppermost 1% of momentum distribution shown!
- Very different vertical scales: Statistics!

Strong development in sensitivities:

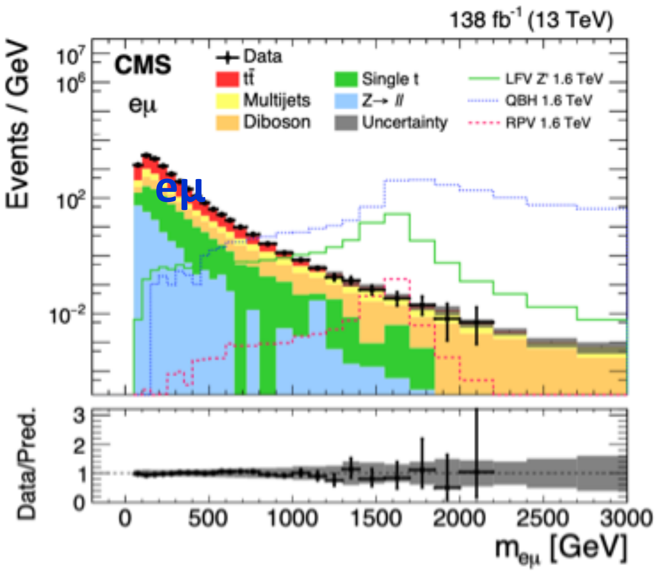
LEP (1995)	HL-LHC (2035)	FCC-ee (2050?)
$\mathcal{B}(Z \to \ell\tau) \lesssim$ **10^{-5}**	$\mathcal{B}(Z \to \ell\tau) \lesssim$ **10^{-6}**	$\mathcal{B}(Z \to \ell\tau) \lesssim$ **10^{-9}**

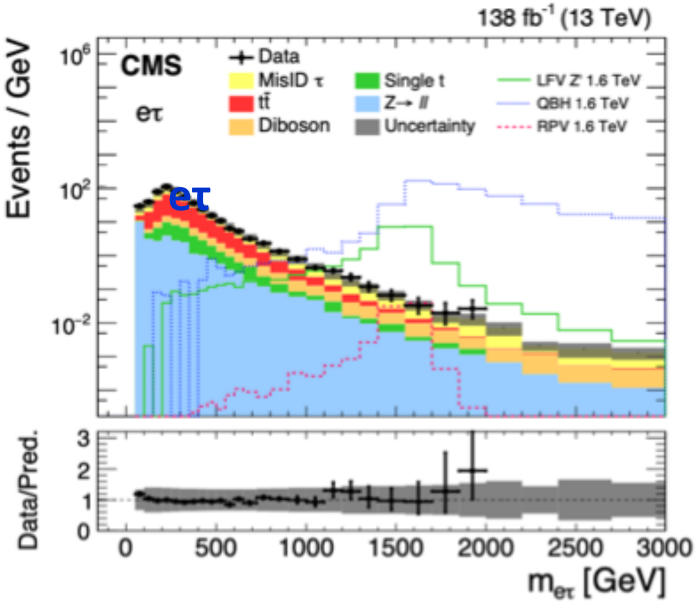
Heavy resonances (e.g. Z') → eμ, eτ, μτ @ LHC

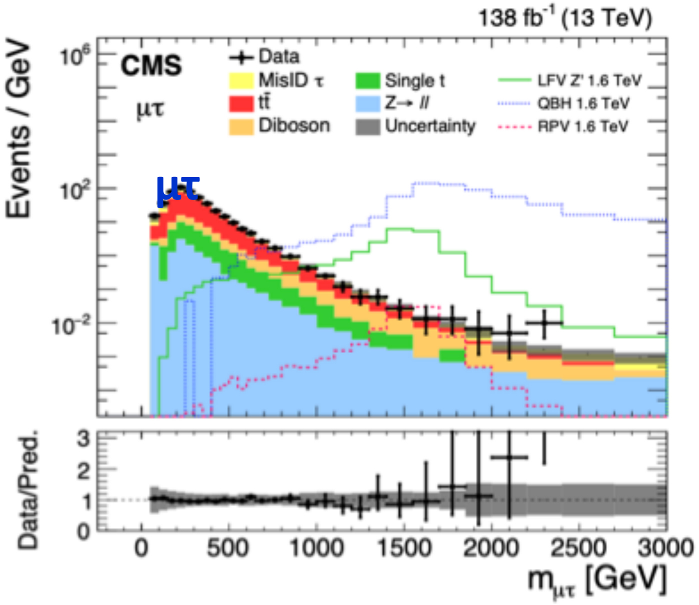
CMS Analysis from full Run-2 dataset [7]



No excess observed







Exclude Z' ($\mathcal{B}$ = 0.1) below: 5.0 TeV 4.3 TeV 4.1 TeV

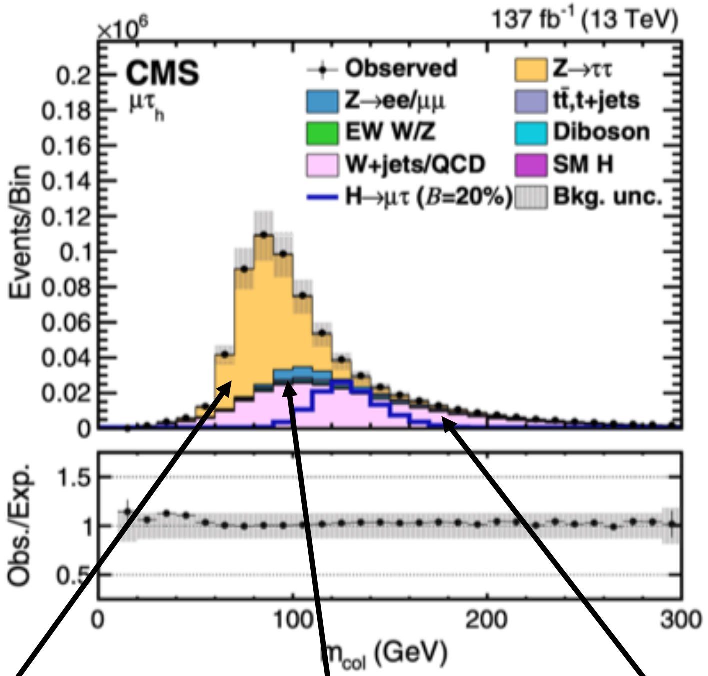
Higgs Decays

$H \to \mu\tau, e\tau$ @ LHC

CMS Analysis from full Run-2 dataset [8]

Search divided into 4 categories:
$\mu\tau_h$, $\mu\tau_e$, $e\tau_h$, $e\tau_\mu$

Shown here: collinear mass for $\mu\tau_h$

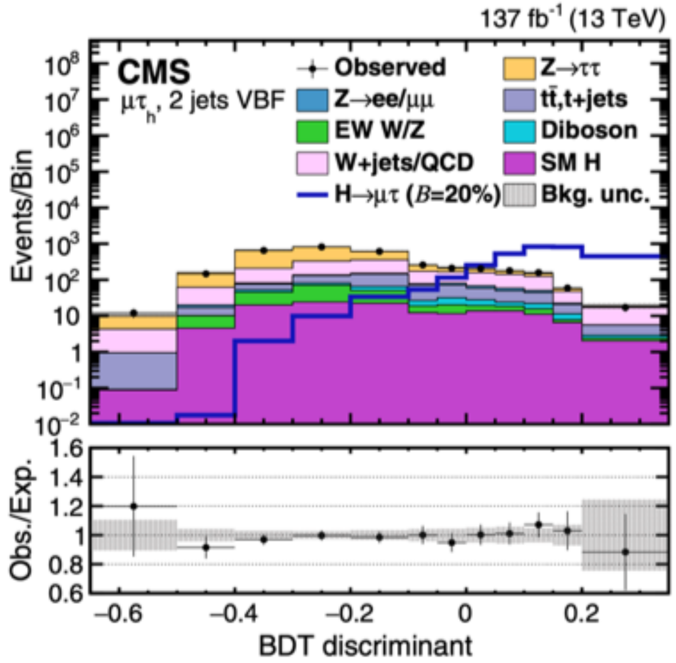


$Z \to \tau\tau$:
Derived from data with data-driven corrections

$Z \to ee/\mu\mu$:
e/μ min-ID as τ_h.
Peaking close to signal
From simulation

Jet $\to \tau_h$ fakes:
QCD and W+jets
Data-driven

Each of the 4 categories further sub-divided into 4:
0 jet, 1 jet, 2 jets gg-fusion, 2 jets VBF
For each, construct BDT discriminant



BDT discriminant based on multiple variables:
p_T^{ℓ}, $p_T^{\tau\text{-vis}}$, m_{col}, $\mathbf{p}_T^{miss}$, $m_T(\tau, \mathbf{p}_T^{miss})$,…

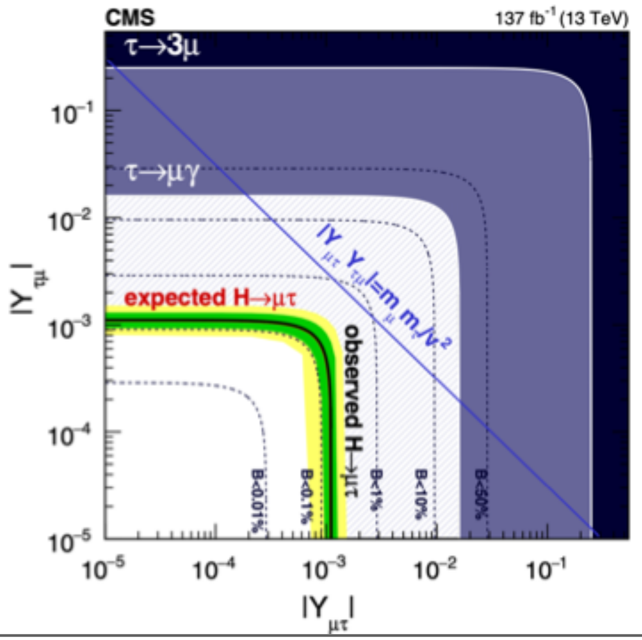
No excess over SM expectation observed. Results from maximum likelihood fit to BDT distributions.

Observed upper limits (95% CL):

$\boxed{\mathcal{B}(H \to \mu\tau) < 15 \times 10^{-4}}$

$\boxed{\mathcal{B}(H \to e\tau) < 22 \times 10^{-4}}$

⇒ Upper limits on Yukawa couplings:



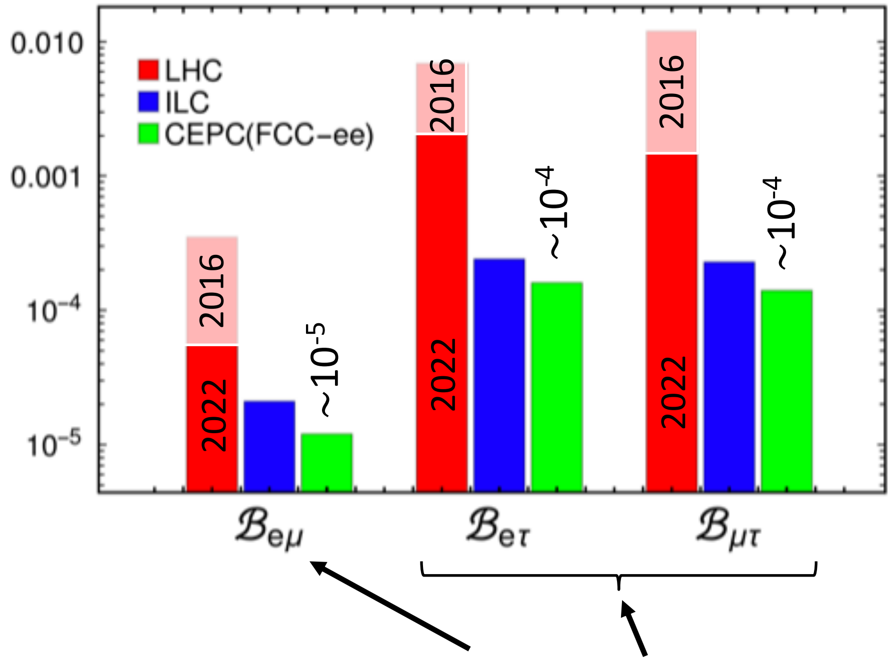
$H \to e\mu, \mu\tau, e\tau$ @ future e^+e^- colliders

[9]

Use Higgs production mode: $e^+e^- \to HZ$ @ 240 (250) GeV

- Statistics:
  - ~ 1 M events at CEPC/FCC-ee (3 years)
  - ~ 0.5 M events at ILC (15 years)
- Exploit dominant (70%) Z decay mode $Z \to qq$
  - Loose requirement on di-jet mass
- $H \to e\mu$
  - Ask $m_{e\mu}$ to be within window around m_H
  - Detection efficiency: 41%
- $H \to e\tau, \mu\tau$
  - Use again only $e\mu$ signature: $e\tau$ ($\mu\tau$) $\to e\mu\nu\nu$
    - Punished by $\mathcal{B}(\tau \to \ell\nu\nu) \simeq 18\%$
  - Reconstruct τ mass from ℓ and $\mathbf{p}^{miss}$; if consistent with m_τ, reconstruct τ momentum from same
  - Ask $m_{\tau\ell}$ to be within window around m_H
  - Detection effeciency: 5%
- In general no (few) background events within signal windows

Results

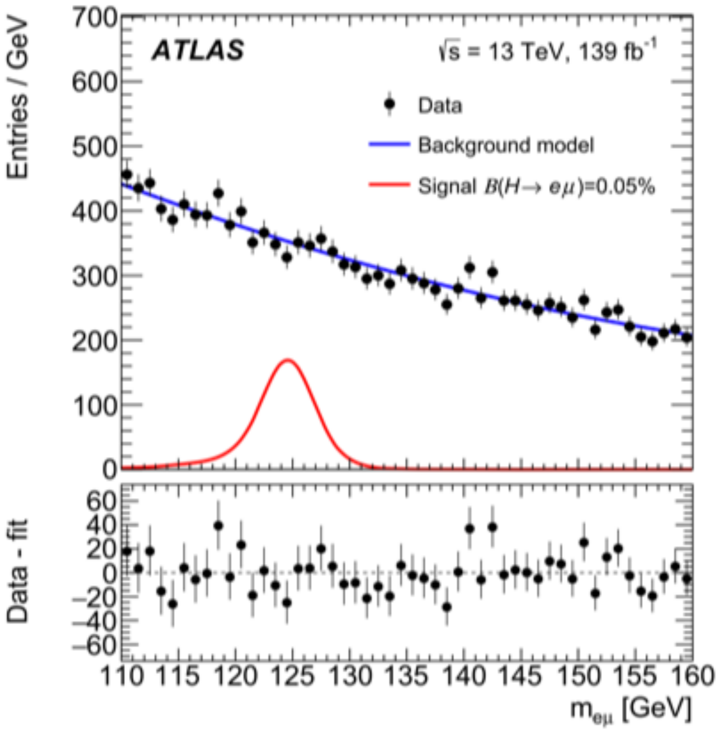


- Difference between $e\mu$ and τ modes due to different detection efficiencies
- Probably potential for improvements from refined analyses including combined discriminating variables.
- However, strongly statistics limited

$H \to e\mu$ | Future of $H \to e\mu, \mu\tau, e\tau$

$H \to e\mu$

ATLAS Analysis from full Run-2 dataset [10]

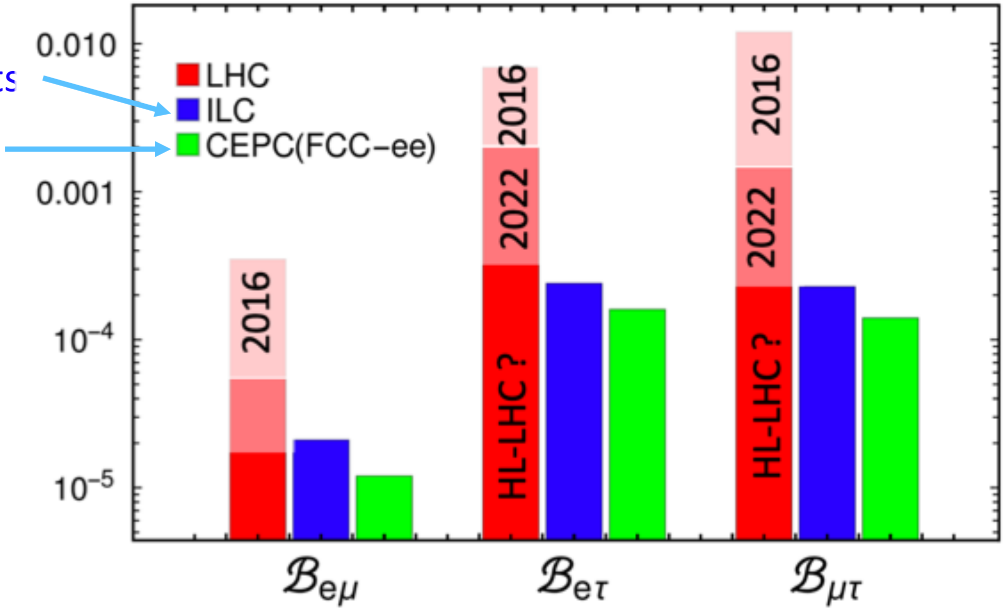


$\mathcal{B}(H \to e\mu) < 6.2 \times 10^{-5}$

Future sensitivities – LHC and e^+e^- colliders

0.5 M HZ events

1 M HZ events



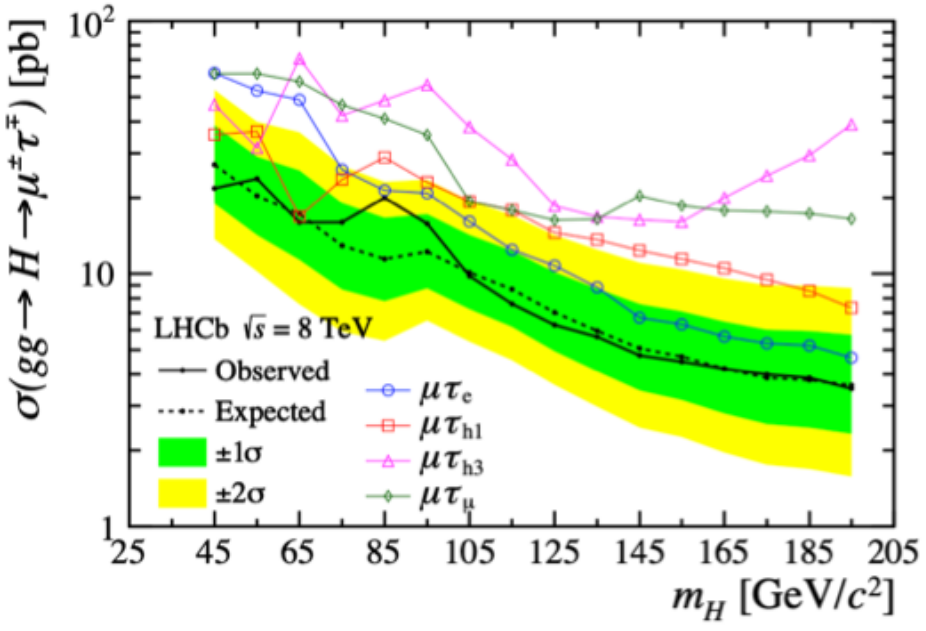
- HL-LHC: Expect factor 5-10 improvements from ×20 larger data samples + refinement of analyses
- Future e^+e^- facilities will be severely statistics limited:
  - Likely, only small improvements w.r.t. HL-LHC

Search for other scalar particles → μτ, eτ

LHCb analysis of 2 fb^{-1} of 8 TeV data
- Targets forward production
- Most sensitive result so far for scalar masses below 125 GeV

CMS analysis of 36 fb^{-1} 13 TeV data
- Analysis strategy close to that focussed on 125-GeV particle

[12]



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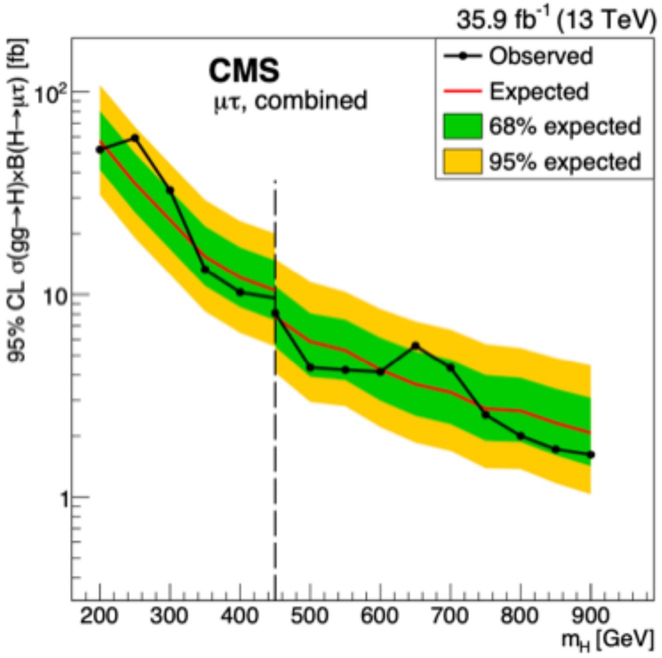
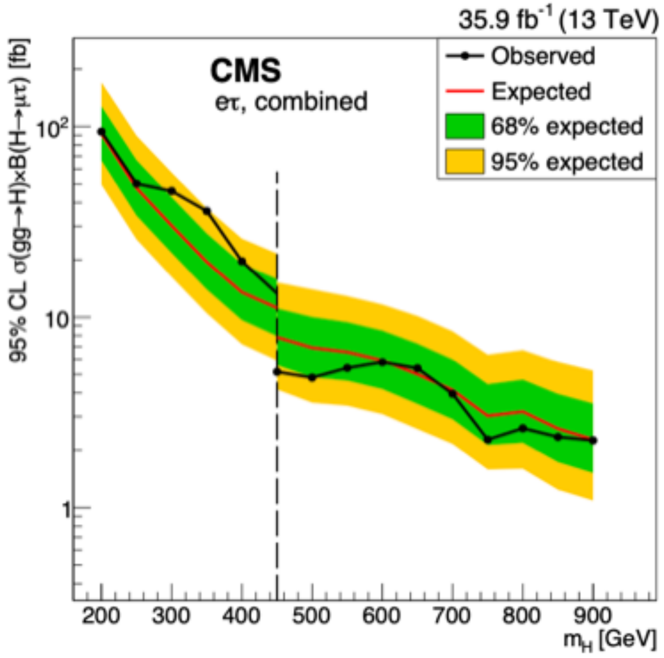


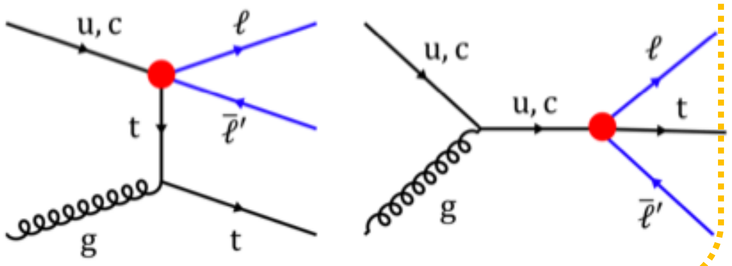


Top quark production and decay

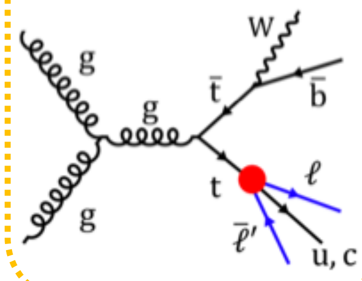
CLFV in top quark production and decay

CMS Analysis from full Run-2 dataset [14]

Production: single top



Decay: ttbar



Combined (BDT) variable to discriminate signal/background

Production channel found to be most sensitive:

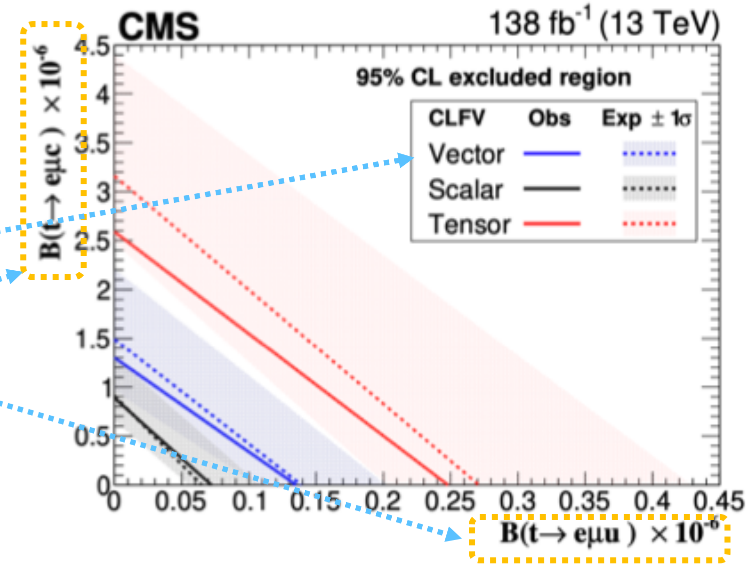
- Higher event yield; harder p_T final state particles

Data consistent with SM:
$\Rightarrow \mathcal{B}$ limits

For different CLFV couplings

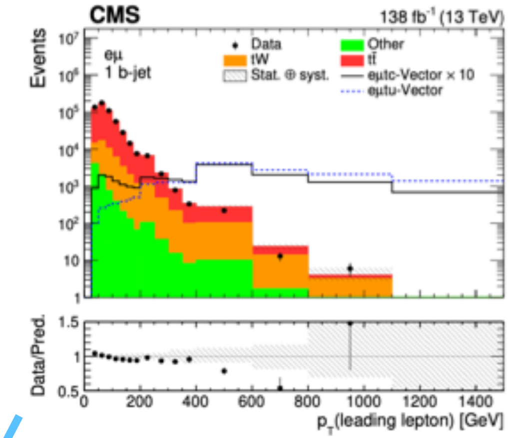
Correlated $\mathcal{B}$ limits

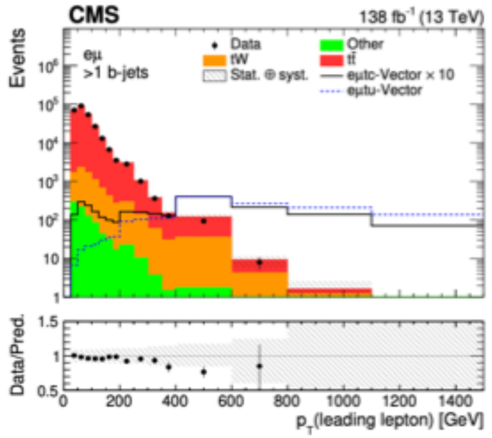
10^{-6} level !



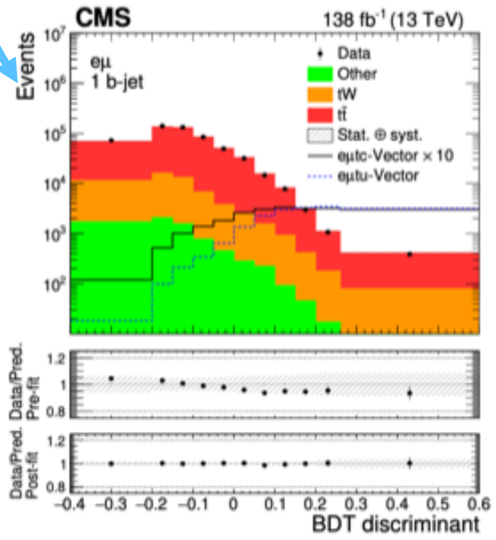
This column: 1 b-jet
Signal region

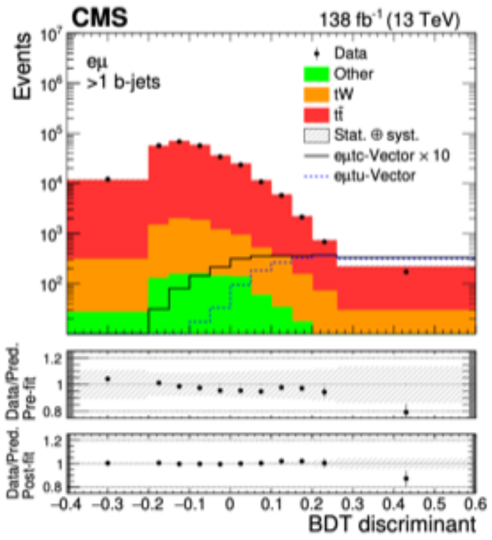
This column: >1 b-jet
ttbar control region





\+ 4 other discriminating variables





Summary & Outlook

Summary & Conclusion

Reminder from slide 5

	LHC Run 2	HL-LHC	FCC-ee
Z bosons	8×10^{9}	1.7×10^{11}	5×10^{12}
Higgs bosons	7×10^{6}	1.6×10^{8}	1.2×10^{6}
top quarks	2.2×10^{8}	5×10^{9}	2×10^{8}

Summary of limits/sensitivities…

	LEP	LHC Run 2	HL-HC	FCC-ee
$Z \to e\mu$	1.7×10^{-6}	2.6×10^{-7}	10^{-7}	$10^{-10} - 10^{-9}$
$Z \to \ell\tau$	10^{-5}	5×10^{-6}	10^{-6}	10^{-9}
$H \to e\mu$	–	6×10^{-5}	10^{-5}	10^{-5}
$H \to \ell\tau$	–	2×10^{-3}	few $\times 10^{-4}$	10^{-4}
$t \to e\mu u(c)$	–	$0.1\ (1) \times 10^{-6}$	$\times 1/5$	no study

References

[1] ATLAS collaboration, *Search for the charged-lepton-flavor-violating decay $Z \to e\mu$ in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector*, 2204.10783.

[2] OPAL Collaboration, *A search for lepton flavour violating Z decays*, Z. Phys. C - Particles and Fields 67 (1995) 555.

[3] M. Dam, *Tau-lepton Physics at the FCC-ee circular e^+e^- Collider*, SciPost Phys. Proc. 1 (2019) 041 [1811.09408].

[4] ATLAS collaboration, *Search for charged-lepton-flavour violation in Z-boson decays with the ATLAS detector*, Nature Phys. 17 (2021) 819 [2010.02566].

[5] ATLAS collaboration, *Search for lepton-flavor-violation in Z-boson decays with τ-leptons with the ATLAS detector*, Phys. Rev. Lett. 127 (2022) 271801 [2105.12491].

[6] DELPHI Collaboration, *Search for lepton flavour number violating Z decays*, Z. Phys. C - Particles and Fields 73 (1997) 243.

[7] CMS collaboration, *Search for heavy resonances and quantum black holes in $e\mu$, $e\tau$, and $\mu\tau$ final states in proton-proton collisions at $\sqrt{s}$ = 13 TeV*, 2205.06709.

[8] CMS collaboration, *Search for lepton-flavor violating decays of the Higgs boson in the $\mu\tau$ and $e\tau$ final states in proton-proton collisions at $\sqrt{s}$ = 13 TeV*, Phys. Rev. D 104 (2021) 032013 [2105.03007].

[9] Q. Qin, Q. Li, C.-D. Lü, F.-S. Yu and S.-H. Zhou, *Charged lepton flavor violating Higgs decays at future e^+e^- colliders*, Eur. Phys. J. C 78 (2018) 835 [1711.07243].

[10] ATLAS collaboration, *Searches for lepton-flavour-violating decays of the Higgs boson in $\sqrt{s}$ = 13 TeV pp collisions with the ATLAS detector*, Phys. Lett. B 800 (2020) 135069 [1907.06131]

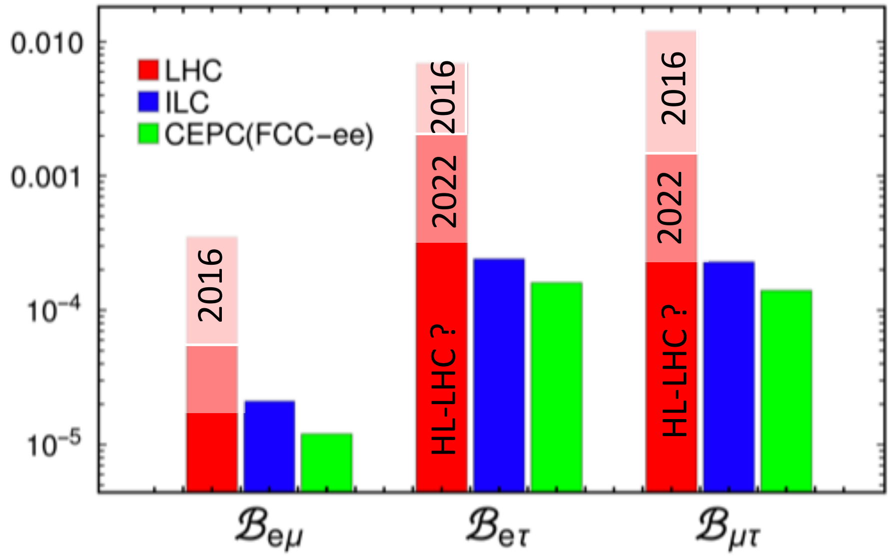
[11] ATLAS collaboration, *Search for the Higgs boson decays $H \to ee$ and $H \to e\mu$ in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector*, Phys. Lett. B 801 (2020) 135148 [1909.10235].

[12] LHCb collaboration, *Search for lepton-flavour-violating decays of Higgs-like bosons*, Eur. Phys. J. C 78 (2018) 1008 [1808.07135].

[13] CMS collaboration, *Search for lepton flavour violating decays of a neutral heavy Higgs boson to μτ and eτ in proton-proton collisions at √s = 13 TeV*, JHEP 03 (2020) 103 [1911.10267].

[14] CMS collaboration*, Search for charged-lepton flavor violation in top quark production and decay in pp collisions at √s = 13 TeV*, 2201.07163

Extras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0.001
10^{-4}
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LHC
ILC
CEPC(FCC−ee)
2016
2022
HL-LHC ?
$\mathcal{B}_{e\mu}$
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